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DESCRIPTION OF THE MARK II ATMOSPHERIC FLUIDIZED BED COMBUSTOR AT THE COMBUSTION AND CARBONIZATION RESEARCH LABORATORY, CANMET

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by

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ABSTRACT

The facilities for fluidized bed research at the Combustion and Carbonization Research Laboratory (CCRL) at CANMET's Energy Research Laboratories near Ottawa were improved when a new larger pilot-scale combustor was made operable in March 1981. The new atmospheric fluidized bed combustor (AFBC) has a cross section of 380 x 406 mm, variable in-bed cooling and is capable of feeding both liquid fuels and a variety of solid fuels up to 50 mm size both in-bed and over-bed. In addition it has the capacity for sulphur sorbent injection and fines recycle.

The equipment replaced a smaller (240 mm diam) and less versatile facility which was described previously. Subsequently the facility was modified substantially and the research program expanded to include a much wider range of fuels. These ranged from coal, coke, biomass, fuel oil, pitches and tars. This report describes the current facility and all changes made in both equipment and operating procedures.

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DESCRIPTION DE L'INSTALLATION DE COMBUSTION EN LIT FLUIDISÉ À LA PRESSION ATMOSPHÉRIQUE MARK 11 SITUÉE AU LABORATOIRE DE RECHERCHE SUR LA COMBUSTION ET LA CARBONISATION, CANMET

par

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RÉSUMÉ

Les installations de recherche sur la combustion en lit fluidisé du Laboratoire de recherche sur la combustion et la carbonisation (LRCC), lequel fait partie des Laboratoires de recherche sur l'énergie (CANMET) qui sont situés à proximité d'Ottawa, ont été transformées par la mise en service d'une nouvelle installation expérimentale de plus grande dimension en mars 1981. La nouvelle installation de combustion en lit fluidisé à la pression atmosphérique possède une section transversale de 380 X 406 mm, une unité de refroisissement réglable à l'intérieur du lit et peut être alimentée soit en déposant les charges directement dans le lit ou au-dessus du lit. L'alimentation peut comprendre des combustibles liquides et une variété de combustibles solides d'une dimension pouvant aller jusqu'à 50 mm. De plus, il est possible de faire des injections de sorbant de soufre et de recycler les fines.

L'équipement remplace une plus petite unité moins versatile (diamètre de 240 mm) qui a déjà fait l'objet d'une description. Par la suite, l'installation a subi d'importantes modifications et le programme de recherche a été intensifié de façon à inclure une plus grande gamme de combustibles, y compris le charbon, le coke, la biomasse, l'huile combustible, les brais, et le gaudron. Dans ce rapport, l'auteur donne une description de l'installation actuelle et des modifications réalisées au niveau de l'équipement et du mode d'exploitation.

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INTRODUCTION

In 1975 the Canadian Combustion Research Laboratory now known as the Combustion and Carbonization Research Laboratory (CCRL) began a program of research and development on atmospheric fluidized-bed combustion (AFBC), and erected a small pilot-scale combustor known as the Mark I combustor. This had an inside diameter of 240 mm and was described in detail in an earlier report (1). It was used to test a wide variety of fuels, (2-5), however, its configuration and small size severely restricted the range of variables which could be explored. Some of its major drawbacks are listed below:

1. Heat input rate was restricted to about 400 MJ/h - too small for reliable extrapolation of results to industrial-size units.
2. The combustor design incorporated an Inconel liner which had a service life of only 100-200 h.
3. The combustor was circular in cross-section, and enclosed by a water jacket which was not typical of full-scale equipment, and made probing of the bed and freeboard regions difficult.
4. There was no in-bed cooling. This made it difficult to control bed temperature and impossible to measure bed-to-tube heat transfer rates.

As both the potential applications of FBC technology to the Canadian energy picture and the need for supporting R & D became apparent, it was decided to support the development of a larger, more versatile pilot-scale combustor at CCRL. The new facility, "Mark II", was developed and was described in detail in an earlier report (6). Subsequently both the unit and operational procedure were modified substantially which made it necessary to produce a new description of the facility. The main features of the unit are as follows:

1. The combustor is approximately square in section (380 mm x 406 mm) and fabricated from refractory brick. This allowed fairly simple construction and substantially more latitude in providing for the insertion of probes.
2. The cross-sectional area, and therefore the maximum heat input rate, is approximately three times greater than that of the Mark I combustor. Reliability in extrapolating results to full-scale is thus increased, although operating costs are still modest.

3. Provision has been made whereby anywhere from 0 to 48 water-cooled tubes can be inserted in the bed including 2 bayonet type retractable tubes. Thus bed heat extraction can be matched to the requirements of a wide variety of fuels at various test conditions, in-bed heat transfer rates can be measured, and corrosion/erosion mechanisms in the bed can be studied.
4. Solid fuel in a variety of sizes up to 50 mm can be fed, either over the bed or directly into it.
5. Sulphur sorbents such as limestone can be fed into the bed at variable rates through a separate feed system. This precludes the need to premix sulphur sorbents with the fuel.
6. Liquid fuels such as number 6 oil can be fed using a pump.
7. Fly ash trapped by a primary cyclone system can be reinjected into the bed to improve the efficiency of carbon combustion and limestone utilization.

With the improved Mark II fluidized-bed combustor, CCRL is in an excellent position to conduct research on the full range of Canadian solid and liquid fuels which may be utilized by this technology, and provide the data-base required for the design and implementation of full-scale FBC systems and industrial FBC programs.

PILOT-SCALE ATMOSPHERIC FLUIDIZED BED COMBUSTOR

GENERAL DESCRIPTION

The Mark II pilot-scale AFBC facility consists of a combustor with a variable number of in-bed water-cooled tubes, a freeboard section tapering to a fixed duct encircled by a water-cooled coil, a cyclone dust collector with means for fly ash recycle, a flue gas cooler, a baghouse, and a stack. To this are added fuel and sulphur sorbent feed systems, blowers to provide air for combustion and cooling, an induced draft fan, and comprehensive instrumentation.

The combustor and freeboard consist of 9 sections stacked one upon anotner, bolted together by means of flanges, with the joints sealed by Fibrefrax rope gaskets and silicone caulking compound. This assembly stands approximately 4.8 m high and has outside dimensions of 0.94 m x 0.97 m. The internal cross-sectional area is constant at 0.15 m^2. Brackets at the lowest freeboard section transfer the weight of the combustor and freeboard assembly

to a framework of tubular steel columns. A major advantage of this centre support system is that the windbox can be readily removed from below, giving access to the distributor plate and the entire combustion shaft, without dismantling any other part of the combustor. Figures 1 and 2 show details of this assembly.

Windbox and Air Distributor

The lowermost section of the combustor consists of a windbox with an air distributor fixed to the top of it. The windbox is constructed of mild steel 6.3 mm thick and is equipped with an explosion relief vent. The air distributor, which forms the floor of the combustion zone, is a steel plate 380 mm square and 9.5 mm thick, fitted with 100 bubble caps for dispersing the air uniformly into the fluidized bed. The bubble caps are arranged in a 35 mm x 38 mm rectangular pitch, as shown in Fig. 3, and those on the perimeter also serve to fasten the air distributor to the windbox. The bubble caps were made from stainless steel bolts 13 mm diam x 32 mm long by drilling an air passage 6 mm diam up the bolt axis and drilling four 3 mm diam air nozzles at right angles under the bolt head, as shown in Fig. 4. With this configuration the bolt head serves as a shield to prevent bed material from weeping through the air passages into the windbox. The air nozzles are located about 20 mm above the plate thus leaving a layer of non-fluidized bed material which thermally insulates the plate from the high temperatures of the combustion zone.

Air for fluidization and combustion is supplied by a centrifugal blower which has sufficient capacity to provide fluidizing velocities up to 4 m/s, at the design firing rate. The air enters the windbox via a pipework system which contains flow metering and control equipment. Pressure drop across the air distributor varies from about 150 mm to 300 mm water gauge at fluidizing velocities from 1 to 3 m/s.

Active Bed Zone

The active bed zone extends for about 1400 mm above the air distributor. For convenience in assembly and maintenance this was fabricated in two sections approximately 750 mm and 650 mm in height. The pressure capability

of tne present fluidizing air blower limits the fluidized-bed depth to about 0.75 m when silica sand in the size range of 0.85 to 1.70 mm is used as bed material, but the splasn zone above the bed must also be considered part of the active bed zone.

Except for the bed tube retainers described later, the active bed zone is lined, with an inner course of 114 mm thick firebrick backed by two courses of 64 mm thick high-density insulating brick. The brickwork is encased by a mild steel shell 6.3 mm thick and about 30 mm of loose insulating material fills the space between the brickwork and the shell. This construction is typical of the freeboard sections as well as the active bed zone, and is shown in cross-section in Fig. 5.

On each of two opposite sides of the active bed zones immediately above the air distributor, is a water-cooled bed tube retainer 650 mm high, 560 mm wide and 127 mm thick. As shown in Fig. 6, the retainers are each penetrated by 48 guide sleeves which have an I.D. of 35 mm and are arranged on an 81 mm triangular pitch. Each sleeve is aligned with its counterpart across the combustor, thus each part provides a path by which a tube can be passed through tne bed. The retainers are set back approximately 75 mm from the inside surface of the combustor and this space is filled, between the guide sleeves, with castable refractory which serves to minimize the heat loss to tne retainers during operation.

Tne amount of neat which must be removed from the fluidized bed to maintain a target bed temperature depends upon the moisture content of the fuel, the firing rate, tne excess air level, the desired bed temperature and the calorific value of tne fuel. While it is expected that the bed cooling requirements of the combustor can in most cases be met with less than 22 cooling tubes, the provision for 48 allows considerable flexibility in vertical and horizontal spacing. This will be useful when research is expanded beyond the measurement of heat transfer rates to studies of boiler tube corrosion in fluidized beds and the effect of immersed tubes on bubble growth.

The cooling tubes are straight sections of stainless steel pipe 15.8 mm I.D. (1/2 in. nominal pipe size) approximately 381 mm long. Two of the cooling tubes are of a retractable bayonet type, with an 8 mm I.D. tube sitting within a 15.8 mm tube. This arrangement enables a variable length (0 to 381 mm) and hence surface area of the cooled tube to be exposed to the bed and permits fine tuning of tne bed temperature. By means of hoses they can be externally connected through flowmeters to a water supply line in series or

parallel circuits as desired. To seal off the combustor where the cooling tubes pass out of the guide pipes, bushings with 'O' rings are used as shown in Fig. 7. The guide sleeves can also be used as ports for measuring probes or fly ash reinjection; unused sleeves are simply capped off with a blank insert to prevent the sleeve filling up with bed material.

Fuel and limestone can be injected into the lower part of the bed through a horizontal feed port located about 100 mm above the distributor plate. The feed mechanism itself is described in a later section. An identical feed port located 1.2 m above the distributor, and thus normally in the freeboard region, can be used when an overbed feed mode is desired.

To maintain a constant bed level during operation, it may be necessary to either add or remove bed material, depending upon the fuel being fired. If for example the fuel is low in ash, attrition and subsequent elutriation may progressively reduce the bed inventory. In that case, additional bed material such as silica sand can be added via the fuel feed system. However, if a high-ash fuel is being fired, or if a sulphur sorbent such as limestone is being added with the fuel, then bed inventory is likely to increase, and removal of bed material is necessary to maintain constant bed level. The Mark II combustor has two means of removing bed material. One is a simple overflow pipe, having its inlet in the combustor wall 1 m above the distributor plate, and inclined downward at an angle of 45° from the horizontal. It automatically maintains a bed height of 1 m, provided that the material collected in the pipe is periodically removed through a valve at the discharge end. The other means for removing bed material is a horizontal pipe penetrating the combustor wall just above the distributor plate. It is equipped with a valve and a manually operated screw, and can be used to maintain any desired bed level.

Three observation ports are located on three sides of the combustor. One consists of a horizontal pipe, 76 mm I.D., located 1.07 m above the distributor plate, opposite the overbed feed port. Its outside end is fitted with a Pyrex glass window and it is serviced with a compressed air line to clear out accumulated bed material and provide cooling. A similarly constructed port, but 76 mm I.D. and inclined at 45° to the horizontal is located at 1.2 m above the distributor plate. It provides a view of the fluidized bed surface. The third port is an 88 x 159 mm rectangle located 813 mm above the distributor plate. It can be fitted with a sapphire window flush with the

inside wall of the combustor, and thus provide a view of bubble or solid movements through the upper region of the bed.

Freeboard

The freeboard region extends above the active bed zone for a distance of about 1.9 m and is made up in three sections, the lowest of which has the supporting lugs for the entire combustor. These sections are fabricated of mild steel and are lined with refractory in a manner identical to activate bed zone, thus they form a near-adiabatic zone in which residual combustion reactions can proceed and elutriated material has an opportunity to disengage from the gas stream.

Finally, a refractory-lined tapered section funnels the flue gases into a discharge spout, to which is attached a 0.25 m diam stainless steel duct encircled by a water-cooled coil. This reduces the flue gas temperature by 200 to 400°C. The tapered section is fitted with several ports through which gas sampling probes and thermocouples are inserted. These make it possible to determine the quantity of heat removed.

Dust Collector and Flue Gas Cooler

The aforementioned duct transports the flue gas, cooling it to between 500 and 600°C, to a small multicyclone dust collector which contains three cyclone elements arranged in parallel. Its nominal performance specifications are 90% efficiency in collecting particles equal to or greater than 10 μm at a pressure drop of 50 mm water gauge. To maintain cyclone pressure drop, and thus collection efficiency, at low gas flowrates, one or two of the cyclone elements can be blocked off. The dust collector hopper has a hopper bottom from which the cyclone product can be removed. The entire assembly is insulated and is suitable for operation up to about 600°C.

Cyclone product discharged from the hopper is collected in a small drum for subsequent analytical work to determine carbon losses. Alternatively, in order to improve carbon combustion efficiency and limestone utilization the cyclone product can be directed into a pneumatic transport system which reinjects it into the fluidized bed.

Gases exiting the dust collector pass into a gas-to-air shell and tube heat exchanger designed to reduce the flue gas temperature to about

120°C. The gases travel consecutively through three vertical passes each consisting of six tubes, 76.2 mm I.D. x 2.8 m long. Fresh cooling air, supplied at the rate of 1.5 m^3/s by a forced draft fan, travels across the tubes from the bottom to the top of the heat exchanger around 9 baffles, as shown in Fig. 8.

Baghouse

At the bottom of the heat exchanger the third gas pass discharges into a duct having an inside diameter of 200 mm and a straight vertical section 2 m long. This is equipped near the upper end with ports through which isokinetic dust sampling can be carried out. The duct terminates at a small baghouse, 0.83 x 1.28 x 2.4 mm high, containing 40 fine-woven cotton sateen filter bags. The baghouse is designed to remove all particles greater than 0.3 µm, at flowrates between 0.14 and 0.38 m^3/s with a pressure drop from 133 to 165 mm watergauge. On-line bag cleaning is accomplisned by means of a motorized shaker. The baghouse storage hopper has a capacity of 0.42 m^3, and it discharges into a double slide gate arrangement which permits on-line removal of the collected fly ash into a closed container.

The foregoing equipment provides for two methods of determining the amount of fly ash which escapes the cyclone dust collector. One method is to determine the dust concentration by isokinetic sampling of the flue gas in the duct joining the heat exchanger to the baghouse, and then performing the appropriate calculations. The other method is to collect and weigh the dust collected by the baghouse during a specific test period. Both methods are able to provide samples which can subsequently be analyzed for components such as carbon, calcium and sulphur.

The flue gases from the baghouse are exhausted to the atmosphere by means of an induced draft fan and a stack. At the time of writing (August 1986) this system is not in use and flue gases are simply exhausted to the stack in a 0.25 m diam pipe by passing both the air cooled heat exchanger and baghouse. It is anticipated that this system will be in use by 1987.

Fuel and Limestone Feed Systems

The fuel and sorbent feed systems monitor and control the feed rate as well as inject the feedstocks into the bed. The fuel bin with vibrating bin discharger feeds the fuel onto a weigh belt feeder. The feeder, with

variable speed motor, is attached to a weight monitor that determines the mass of coal on the belt and adjusts the belt speed to maintain accurately set feed rate on a remote station. This adjustment occurs thirty times per second thus ensuring an accurate flow of fuel into the bed. A similar system is used to feed the sorbent. Both systems are connected to an air lock valve which discharges into a flexible fibreglass hose and then into the bed by means of a variable speed water cooled screw. The screw is water cooled to protect it from the high temperatures of the combustor. The fuel can be injected into the combustor through either the in-bed or overbed feed port. The feed port that is not in use is blocked off by means of a refractory plug, flush to the inside wall of the combustor, and a gasketed flange cover. The maximum feed rates for coal and sorbent are 220 and 70 kg/h respectively. The fuel bin has a capacity of about 1100 kg of coal and the sorbent bin has a capacity of about 700 kg of limestone.

Liquid fuels are fed by means of a pump. The fuel is first heated to decrease viscosity (for easier pumping) and then pumped into the fluidized bed.

The feed system for heavy liquid fuels, such as number 6 oil, consists of a heated storage tank or drum, heated transport lines, a positive displacement pump and a nozzle injector, as shown in Fig. 9. The tank or the drum is placed on an electronic weigh scale to measure the feed rate by noting the change in the weight in a given time. The pump has a volumetric discharge capacity of up to 41 L/h and the feed rate can be varied by adjusting the volumetric flow through the pump.

The nozzle injector is shown schematically in Fig. 10. It consists of two concentric tubes supplying oil and atomizing air. The oil passes through the central tube and the air through the outer tube, entering the combustor at 127 mm above the distributor. The air is preheated before it reaches the injector by passing it through two unused cooling tubes in the bed. For number 6 oil the oil pressure and temperature at the discharge of the pump are about 565 kPa and 70°C respectively. There is also a provision to flush the system with number 2 oil after the test.

Instrumentation

The instrumentation system for the Mark II pilot-scale combustor has been designed to extract as much useful data as possible, and to record it

automatically onto floppy disks using a Hewlett Packard Automatic Data Acquisition Control System. A datalogger is also used for backup purposes.

The fuel and sorbent feed rates are measured and controlled with weigh feeders and hopper with vibrating bin discharger as described in the foregoing section. Fluidizing air flow is measured by means of a calibrated orifice; the pressure across the orifice can be measured by a sensitive manometer, and is recorded as well by a pressure transducer, which sends readings to the computer for interpretation and transformation into flow rate data.

The flow of water through the various circuits, which cool the bed heat exchange tubes, the fuel delivery screw, and the bed tube retainers is measured by electronic turbine flow meters (which send reading to the computer similarly to the pressure transducer) as well as by a bank of rotameters shown in Fig. 11.

Concentrations of CO, CO_2, SO_2, O_2 and NO_x are continuously monitored by a bank of analyzers shown in Fig. 12. The CO, CO_2 and SO_2 analyzers operate on the non-dispersive, infrared (NDIR) principle, the NO_x analyzer operates on a chemiluminescence principle, while the O_2 analyzer is of the paramagnetic type. A second SO_2 analyzer based on UV principle is used for comparison purposes. Air and gas pressures, at the various locations listed in Table 1, are measured by a scanning valve and pressure transducer while the temperatures of each circuit are measured by the thermocouples. All data are recorded every five minutes by the data acquisition system, connected to an HP desk top computer, on floppy disks.

This method of storage enables fast access to data, as well as an easy method for data manipulation with various programs developed to simplify calculations and to present data graphically and in tabular form.

Gas Sampling System

The gas sampling system is simple and reliable. Simplified, the flue gas is filtered, kept at about 100°C, and run through a cooling bath where the condensate is collected and the gas sample is passed through the instruments (see Fig. 13).

The primary filter is an H grade porous stainless steel filter with a pipe fitting used to allow easy installation. It is installed above the flue

in a cylinder, with a pipe at the bottom that protrudes into the centre of the flue. This keeps the filter out of the high temperature zone in the duct and the vertical pipe allows some of the dust to drop out of the gas stream before impinging on the filter. A pipe fitting is also installed at the bottom of the cylinder to allow dust to be blown out with compressed air.

The heated sample line from the filter is then run through a heated box containing two additional filters. It is kept at about 90°C to avoid condensation, and stainless steel tubing is used to prevent corrosion in the event of acid deposition.

The gas sample exits the heated box and goes directly into a simple diaphragm vacuum pump which pressurizes the gas delivered to the instruments with a minimum flow rate of 0.14 m^3/h (5 scf/h) at 15°C and atmospheric pressure.

The sample passes through an inclined stainless steel tube in a constant temperature cooling bath, through a Teflon tube to a moisture trap and then to the instruments via flowmeters. The moisture trap is placed in a cooling bath to ensure the condensate stays in liquid form. The gases then go through a final filter of 0.05 µm to protect the instruments. Teflon tubing is used to ensure that no SO_2 absorption occurs.

For spanning the instruments the gas sample conditioning train is bypassed and the span gas is passed through the instruments directly. By doing this the calibration of the instruments is ensured without interference from any residual gases in the sample line, especially SO_2.

STARTUP AND OPERATING PROCEDURE

The first step in starting up the pilot-scale combustor is to charge it with bed material. Silica sand from 0.85 to 1.70 mm is normally used, and it is charged via the inclined viewport to provide a slumped bed depth of 0.5 to 0.6 m. Then, to protect from overheating, an adequate water supply is established to all the cooling circuits. Next the I.D. fan and F.D. fan are started, all the instruments are switched on and the analyzers calibrated.

In order to bring the bed into service it must first be preheated to the ignition temperature of the fuel. Usually 700°C is sufficient. This is accomplished using a gas-fired burner. Air flow is set at the minimum fluidizing velocity, and the gas-fired burner is ignited. The time of light up of

the gas-fired burner to the time taken to raise the bed temperature to about 700°C is approximately one hour.

When the bed temperature has risen to the ignition temperature of the fuel (typically 600-700°C), the fuel feed system is brought into service at a low rate and the air flow is increased to slightly above the minimum fluidizing velocity. A rapid rise in bed temperature signifies fuel ignition and the burner is switched off. Feed rate and air supply are then adjusted toward the designated test levels, and re-adjusted as necessary as the combustor approaches thermal equilibrium.

Once the combustor has reached equilibrium at the specified input conditions, data recording and performance of specialized test procedures such as dust sampling can commence. Adjustments are required from time to time to maintain the desired input conditions such as fuel feed rate, excess air level and bed temperature. The fuel feed rate may vary due to inconsistencies in fuel size consist or moisture content, and 'hang-ups' in the fuel hopper may have to be overcome. Bed temperature is usually a major input parameter and its control requires close attention. It can be controlled by adjusting fuel feed rate, excess air level, cooling water flow, and the number of in-bed heat exchange tubes and also by means of 2 retractable cooling tubes, described earlier. The first two of these are normally input parameters themselves controlled within narrow limits, hence their usefulness in controlling bed temperature is limited. More commonly, large changes in bed temperature are achieved by changing the number of cooling tubes, while fine tuning is accomplished by adjusting the flow of cooling water or the depth of insertion of the two retractable cooling tubes.

The combustor shutdown procedure is simple. The fuel and limestone feeders are shut off, and when the delivery screw has had time to run empty it too is shut off. The flow of fluidizing air and cooling water are maintained until the bed temperature drops to about 200°C, which takes about 30 min. Then air, water and all instrumentation can be safely turned off. Cooling gradients have been found to be sufficiently gentle that no damage to the combustor refractory results. Alternatively, once fuel feed has been stopped and bed temperature has begun to fall, the bed can be hot-slumped by turning off the fluidizing air blower. In this case a small flow of cooling water is maintained to prevent overheating of the delivery screw, the bed cooling tubes, and bed tube retainers. The hot-slump procedure is used if the

combustor is to be operated again within a few hours, using the same charge of bed material. The bed, when hot-slumped, cools very slowly, and it is possible to re-start some hours later by simply re-fluidizing the bed and initiating fuel feed.

PERFORMANCE PREDICTIONS

In designing test programs it is necessary to predict several aspects of the combustor performance, ranging from relatively simple matters such as the fuel feed rate required to achieve a selected heat input, to more complex matters such as the bed heat exchange surface required. The following example illustrates the procedure.

The heating value of a test fuel is normally determined before combustion tests begin. Calculating feed rate (kg/h) is then a matter of dividing the desired heat input rate (MJ/h) by the heating value (MJ/kg). If the moisture content as fired differs from the moisture content as received, the appropriate correction must be made. The combustor was designed for a maximum heat input of 1400 MJ/h at 20% excess air, and this defines the upper limit on feed rate. Table 2 gives the heating values and maximum feed rates for a number of fuels which have been studied at CCRL. The initial deformation temperature of the ash, as determined by the ASTM ash fusion test, is also required as this defines the upper limit of the bed temperature that can be employed for each fuel.

Calculation of the required bed heat exchange surface involves, for each case, determination of a heat balance for the entire combustor. The heat losses are as follow:

- sensible heat in dry flue gas
- latent and sensible heat in fuel moisture
- radiation from the combustor surface
- convection from the combustor surface
- losses to cooling water in bed tubes, bed tube retainers, and delivery screw water jacket

This ignores minor losses such as sensible heat in the fly ash, sensible heat in drained bed material, and superheat of moisture in the combustion air. The cooling water losses can be determined by calculating the first

four losses listed, and subtracting from the heat input, assuming, at this stage, no loss due to unburned carbon.

To calculate the losses, the ultimate analysis of the fuel must be known, and a number of assumptions must be made. For this example, a subbituminous coal called Highvale has been chosen; its ultimate analysis and heating value are given in Table 3. The assumptions made are listed in Table 4, and it can be seen that some of these, such as bed temperature, coal feed rate, and excess oxygen level, are in fact test input parameters. Additional assumptions are that the entire bed and freeboard are at a uniform temperature, that the combustor exterior has a uniform emissivity, and that the exterior surface area of the combustor is defined by the overall outside dimensions; that is, no correction has been made for protruding ports and flanges.

Calculations on this basis, using established engineering procedures, lead to the heat loss distribution given in Table 5, which shows that for this specific case the cooling water losses amount to 52% of the heat input. Subsequent measurements have shown the calculations to be accurate within 10%.

The cooling water losses, as previously noted, are divided among the bed tubes, the bed tube retainers, and the delivery screw water jacket. The last two of these are fixed in area, whereas the first is variable, and the purpose of the calculations is to determine what area should be installed for a specific set of test conditions. Further calculations lead to the results summarized in Table 6, which shows that for the specified conditions, a bed tube area of 0.177 m^2 is required, which can be provided by 10 tubes.

In the course of a test program with a single coal, the number of bed tubes required may change several times as heat input, bed temperature and excess air level are varied according to the test matrix. The correct number of tubes can of course be determined experimentally, but this is time-consuming, and it has been found more expedient to develop a computer program to perform the calculations outlined in the foregoing. As further operating experience identifies refinements to the assumptions on which the calculations are based, the dependability and accuracy of the prediction method will be improved.

SUMMARY OF TEST CAPABILITIES

The capabilities of the Mark II fluidized bed combustor are summarized in Table 7, in terms of what input conditions can be handled, and what measurements can be taken.

The bin with vibrating discharger, weigh feeder and conveying screw have been found to satisfactorily feed coal or coal-like materials. This system is not ideally suitable for materials such as wood waste which tend to pack and jam in the hopper and small screw feeders. However, attempts to feed and burn heavy liquid fuel have proven to be successful utilizing a pump and heated storage tank.

The present system for recycling fly ash from the cyclone dust collector has also performed satisfactorily. In situations where the recycle rate is several times the fuel feed rate it is necessary to divert part of the flow to a drum, sitting on an electrical weigh scale via a two-way adjustable valve.

The fate of sulphur in the fuel is in many cases adequately traced simply by monitoring the SO_2 content of the flue gases. However, a complete sulphur balance can be carried out by determining the weight and sulphur content of the bed residue and the fly ash streams. CCRL has acquired analytical equipment to rapidly determine the sulphur content of fuel and ash samples for this purpose.

The carbon balance is almost always important, since it defines the combustion efficiency. It requires measurement of the weight and carbon content of each ash stream. The bed residue and cyclone product can be collected and weighed directly; the fly ash escaping the cyclone can be collected in the bag filter and weighed, or it can be calculated from batch-type in-situ dust loading measurements, using the sampling train shown in Fig. 14.

An example has already been given of how the thermal balance can be established. The ability to vary the number of bed cooling tubes is one of the most significant features of the combustor design, and instrumentation is such that bed-to-tube heat transfer rates can readily be determined.

The ability to conveniently change bed tubes makes the combustor an excellent facility for studying high-temperature corrosion phenomena in fluidized beds. CCRL is not planning any work of this nature in the immediate

future, but a probe to measure the partial pressure of oxygen in the bed has been acquired and will be used, during the course of combustion performance evaluations, to generate information on the gaseous environment in the bed.

CONCLUSIONS

It is a common misconception that the role of research and development is completed when a new technology reaches the stage of commercial utilization. In fact, the need for R & D usually continues as long as the technology is in use. A good example of this is provided by CCRL's activities in pulverized-coal-firing technology. Even though this technology has been the standard means for burning coal in large steam generators for over fifty years, R & D effort has had to be increased steadily to meet the new challenges presented by the need to utilize new and often lower-grade coals, the need to broaden the fuel specifications for existing equipment, and the need to meet increasingly stringent environmental regulations.

A similar situation is expected to develop with respect to fluidized bed combustion tecnnology. Its potential role in the Canadian energy picture is large. It includes the environmentally-acceptable utilization of high-sulpnur coal, nigh-ash coal wastes, relatively unreactive coke or char by-products of oil sand extraction, and biomass fuels such as wood waste. It may well expend into tne development of more efficient cycles for thermal generation of electricity. The role of R & D will by no means be ended when the first commercial FBC boiler is successfully commissioned. Each new fuel, each new sorbent, virtually every application will present new problems.

The pilot-scale research facility described in this report, having excellent flexibility in terms of input conditions and extensive instrumentation and measurement capabilities, provides a powerful and important tool for fostering the rapid development of FBC to its optimum role in Canada.

ACKNOWLEDGEMENT

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Table 1 - Thermocouple and pressure probe locations

Thermocouple No.	Location*	Pressure port No.	Location*
1	-6	1	Windbox
2	55	2	127
3	130	3	318
4	200	4	dust collector inlet
5	320	5	pressure drop across dust collector
6	550	6	pressure drop across air supply orifice plate
7	610		
8	760		
9	880		
10	1190		
11	1470		
12	2130		
13	2440		
14	3260		
15	water inlet		
16	RS tube retainer inlet		
17	LS tube retainer inlet		
18	freeboard cooling coil outlet		
19	delivery screw outlet		
20	air supply entering W/B		
21	air supply upstream of orifice plate		
22	cyclone outlet		

*Numbers refer to distance from top of nozzles (mm)

Table 2 - Maximum feed rate and heating value for several fuels

Name	Rank	Heating value (as received) MJ/kg	Feed rate kg/h	Initial ash deformation temperature °C
Onakawana	Lignite A	12.94	108	1149
Klimax	Lignite A	15.17	92	1110
Coalspur	Sub-bituminous B	24.58	57	1327
Judy Creek	Sub-bituminous B	15.81	89	1316
Highvale	Sub-bituminous B	20.84	67	1271
Hat Creek	Sub-bituminous C	19.46	72	1380
Luscar	Sub-bituminous C	26.17	53	1188
Line Creek	M.V. Bituminous	28.24	50	1482
Sage Creek	M.V. Bituminous	26.38	53	1366
Minto	M.V. Bituminous	25.79	54	1093
Syncrude	Coke	26.17	53	1277
Suncor	Char	33.56	42	1304
Wood	--	14.35	98	--
Peat	--	14.50	97	--

Table 3 - Coal characteristics used for the example heat loss calculations

Ultimate analysis	
Name	Highvale
Rank	Sub-bituminous
Composition	wt % (dry basis)
Ash	16.02
C	63.54
H	2.54
N	0.78
S	0.24
O (by diff.)	16.88
Heating value (dry)	24.31 MJ/kg
Moisture	15%

Table 4 - Assumptions for the example heat loss calculations

Location	Temperature °C	Heat transfer coefficient kJ/h m^2 °C
Ambient	25	-
Bed and freeboard	900	-
Outside combustor wall	50	-
Bed tube retainer wall (inside)	150	-
Bed to combustor wall	-	5.4
Bed to water	-	1500*
Cooling water inlet	4	-
Cooling water outlet (max)	80	-
Exposed area of combustor = 13.4 m^2		
Emissivity of combustor wall = 0.65		
Coal feed rate (dry) = 30 kg/h		
Excess O_2 in flue gas = 5%		

*Based on inside surface area of tube

Table 5 - Heat loss distribution resulting from the example heat loss calculations

Source	% of Input
Loss to flue gases	37.0
Moisture loss	1.7
Convective loss	8.6
Radiation loss	0.7
Cooling water losses (by diff.)	52.0
	100.0

Table 6 - Distribution of cooling water losses and bed tube requirements resulting from the example calculations

Total cooling water flow required	19.9 L/min
Distribution of cooling water losses	% of total
Bed tube retainers	40.0
Delivery screw water jacket	1.0
Bed tubes	59.0
	100.0
Bed tube cooling water flow required	11.7 L/min
Bed tube area required	0.177 m^2
No. of bed tubes required (12.7 mm nom. pipe x 380 mm)	10

Table 7 - Summary of capabilities of the Mark II combustor

Input capabilities

- Burns coal or coke with a particle size range up to 50 mm, also burns heavy oils and biomass
- In-bed or over-bed feed
- Separate limestone feed to provide a wide range of Ca/S molar ratios
- Bed depth to 1 m
- Bed temperature range 700 to 1200°C
- Heat input range 500 to 1400 MJ/H
- Excess O_2 in flue gas range 0 to 10%
- Superficial fluidizing velocity range 1 to 4 m/s
- Optional recycle of fly ash from cyclone dust collector
- Bed heat exchange area range 0 to 0.90 m^2 (inside surface area) (0 to 48 tubes)

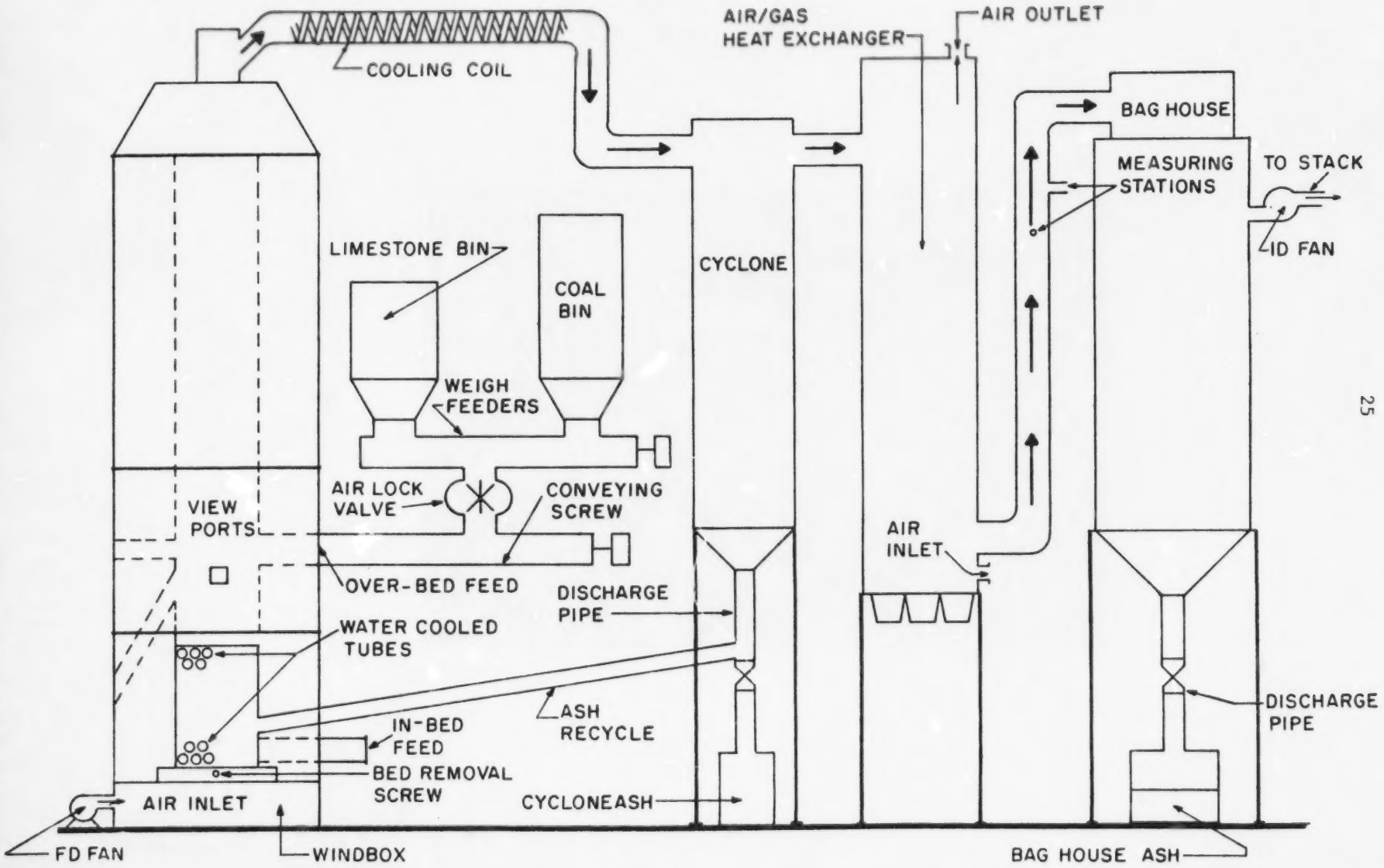
Measurement capabilities

- Complete sulphur balance
- Complete carbon balance
- Complete solids balance
- Complete thermal balance, including measurement of heat extracted by the bed cooling tubes and determination of heat transfer coefficients between the bed and cooling tubes
- Continuous flue gas analysis for CO_2, CO, O_2, SO_2 and NO_x
- Temperature throughout the system
- Pressure throughout the system

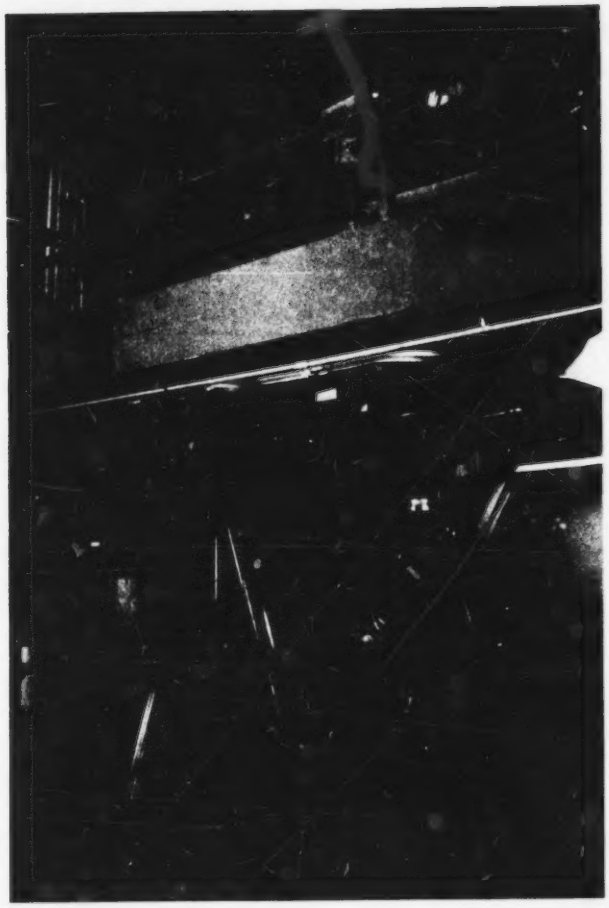
Table 8 - Range of operating conditions*

Parameter	Range
Input	
Bed temperature	700 - 1100°C
Heat input rate	500 - 1400 MJ/h
Excess O_2 (in flue gas)	2 - 10%
Fluidizing velocity	1 - 4 m/s
Ca/S molar ratio	0 - 5
Output	
CO concentration	100 - 1000 ppm
CO_2 concentration	10 - 18%
NO_x concentration	50 - 200 ppm
SO_x concentration	200 - 7000 ppm
Elutriated material	
Ash	75 - 100%
Limestone	0 - 30%
Bed material	0 - 10%

*Output parameters will be dependent on coal composition



SCHEMATIC OF MARK II COMBUSTOR FIG 1

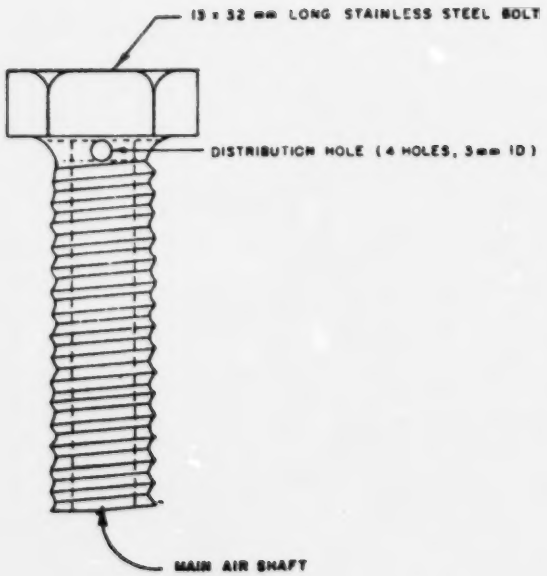


VIEW OF THE MARK II COMBUSTOR

FIG 2

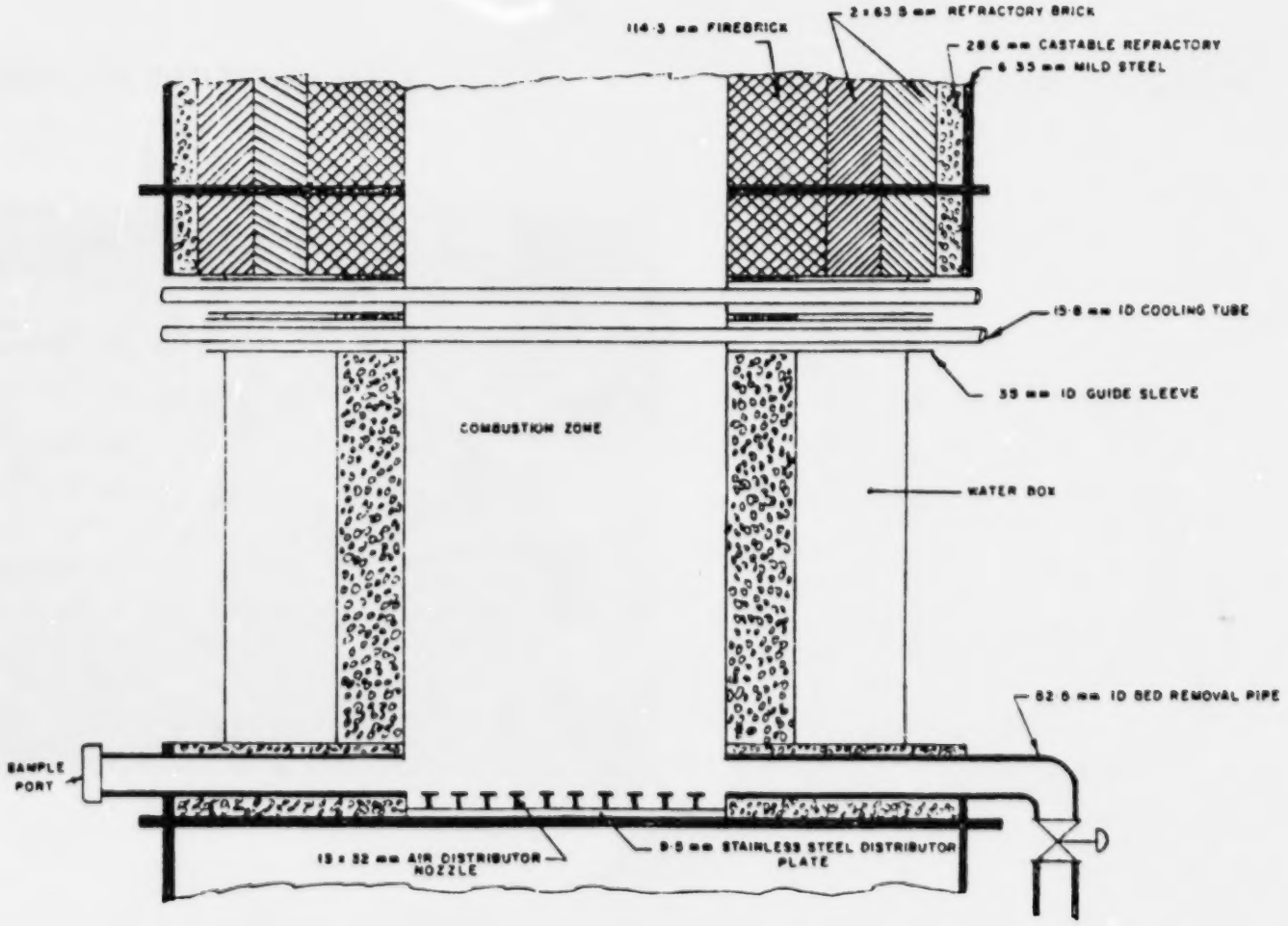
ARRANGMENT OF DISTRIBUTOR PLATE

FIG 3



DETAIL OF AIR DISTRIBUTION NOZZLE

FIG 4

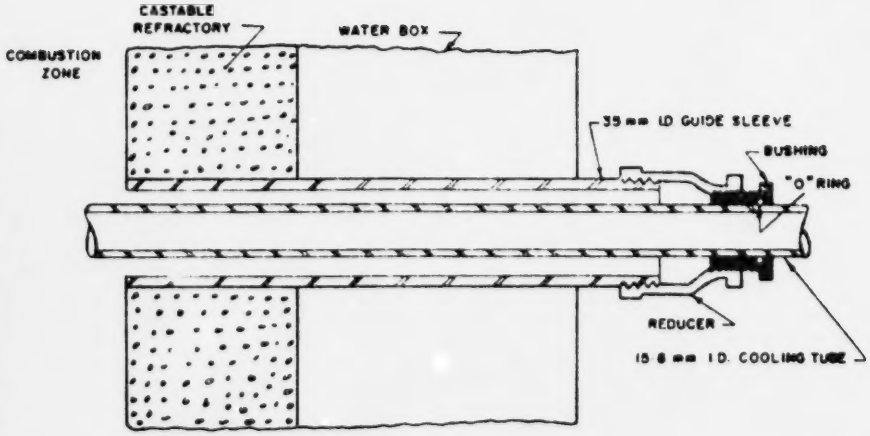


CROSS–SECTIONAL VIEW OF ACTIVE BED ZONE

FIG 5

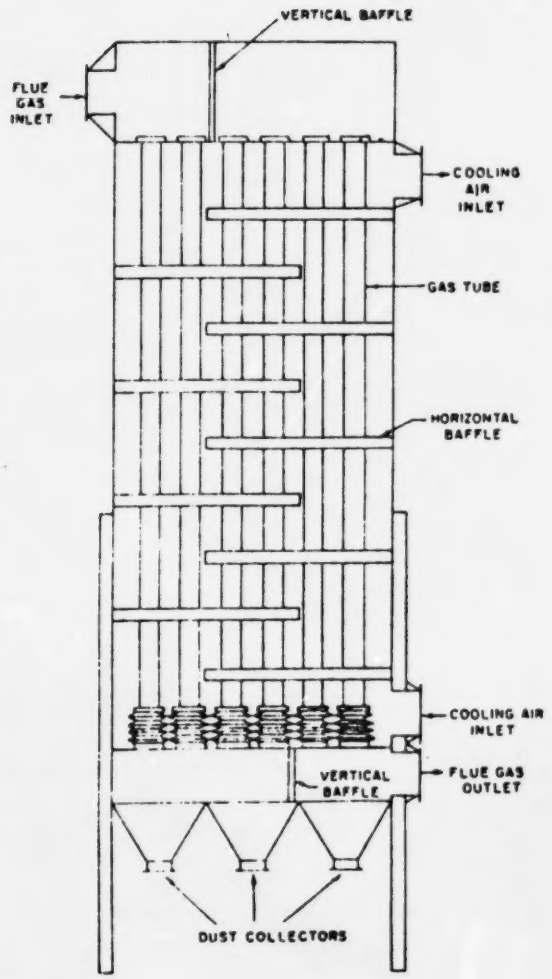
VIEW OF WATERBOX ARRANGEMENT

FIG 6



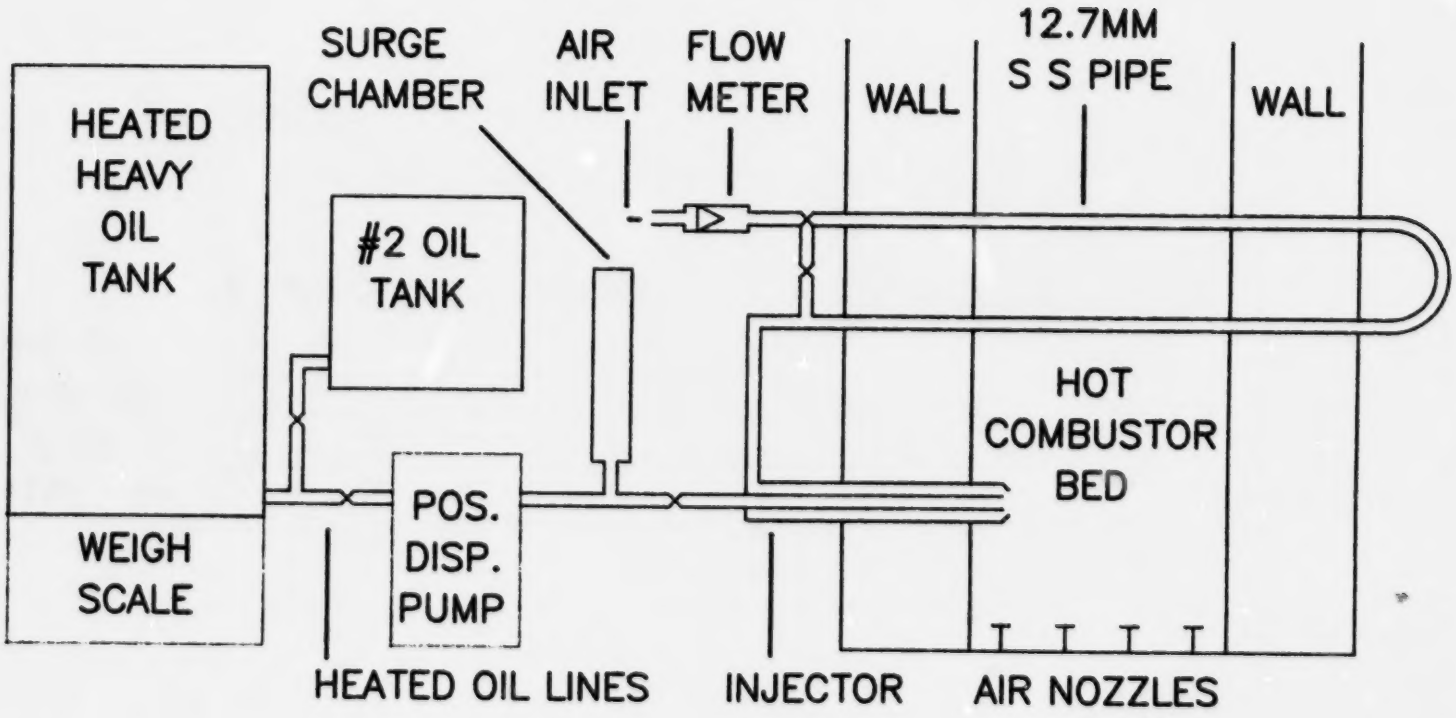
ISOLATED VIEW OF COOLING TUBE ARRANGEMENT

FIG 7



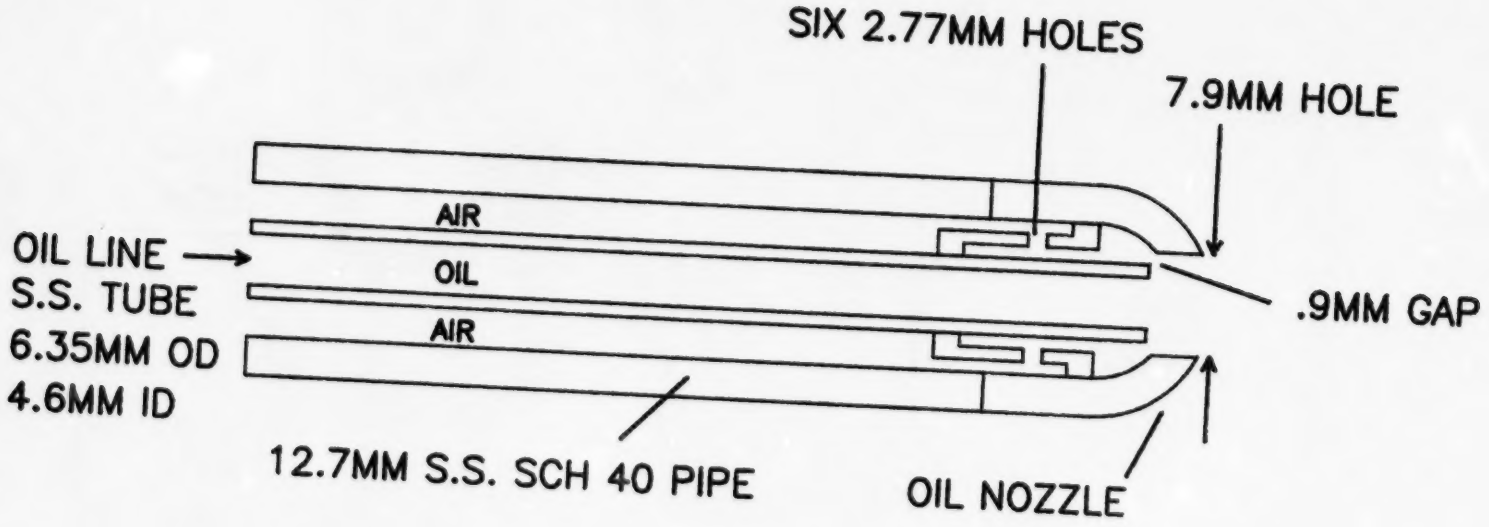
CROSS–SECTIONAL VIEW OF GAS/AIR HEAT EXCHANGER

FIG 8



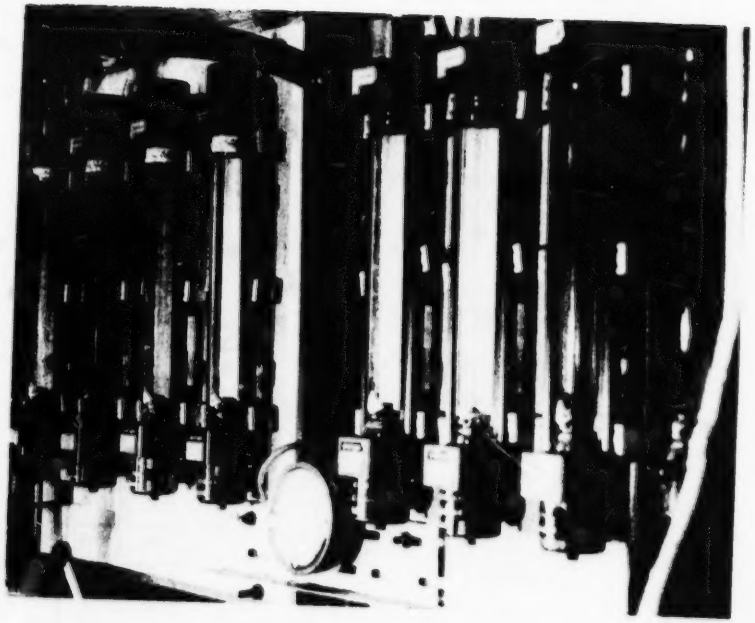
FEED SYSTEM
FOR HEAVY LIQUID FUELS

FIG 9



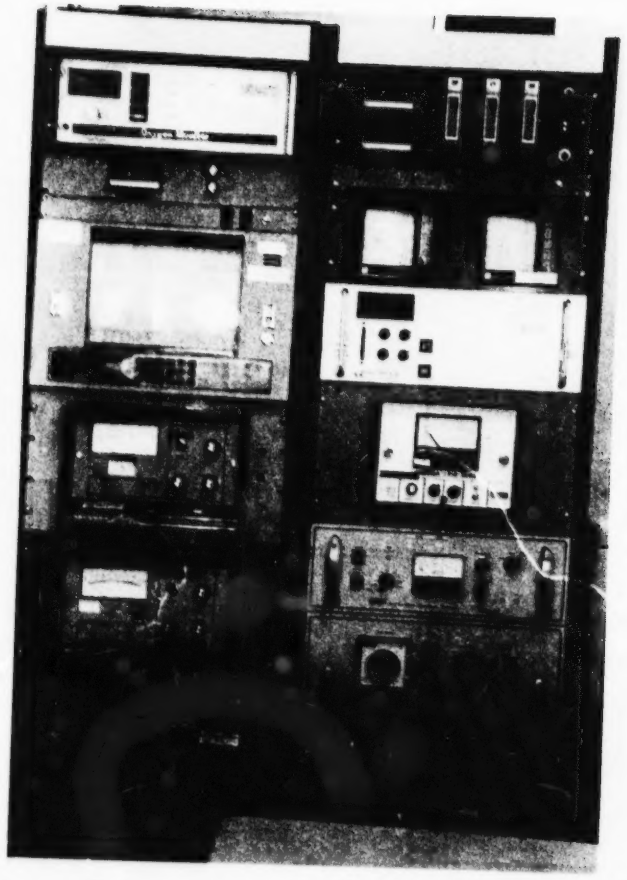
HEAVY LIQUID
INJECTOR NOZZLE

FIG 10



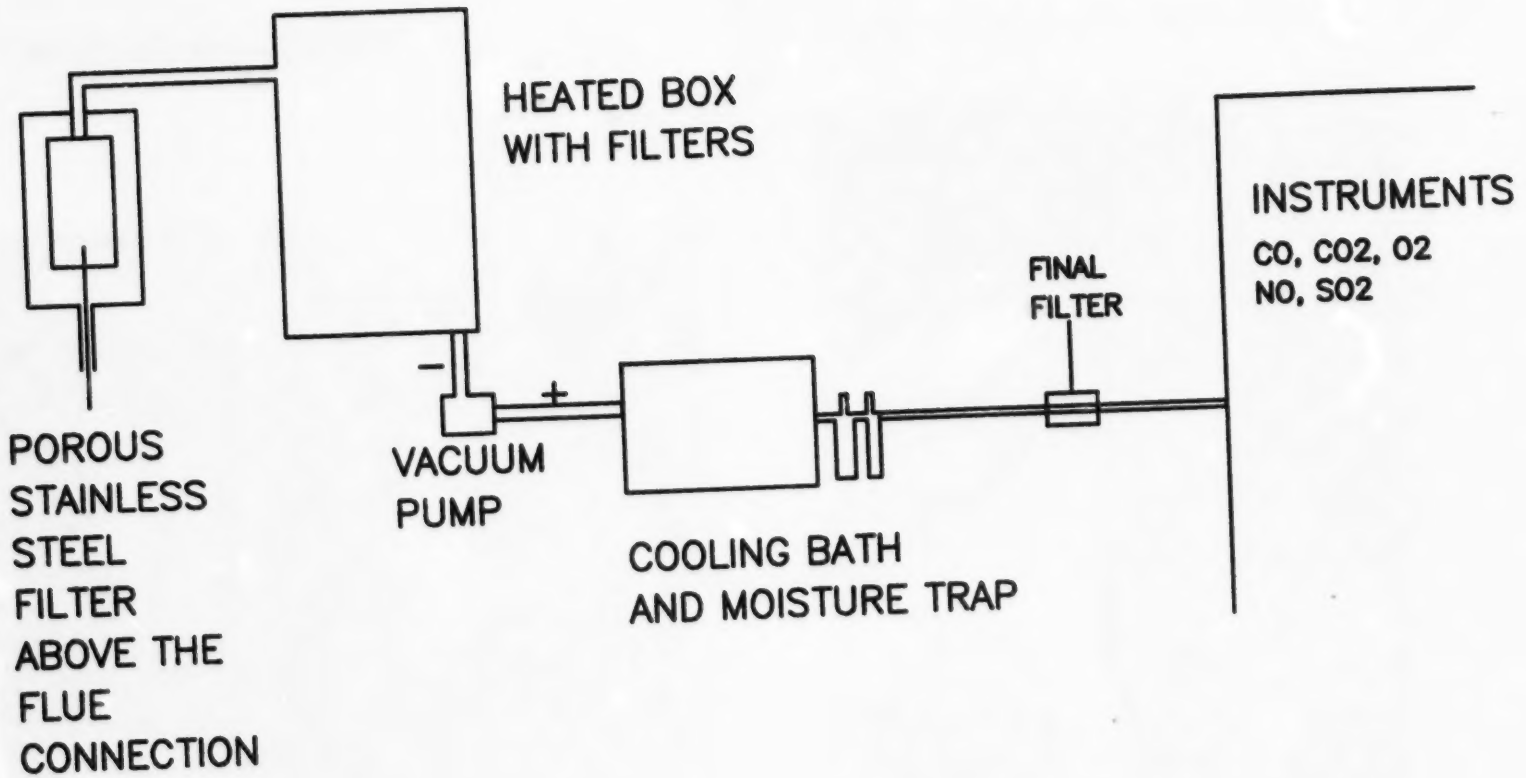
WATER FLOWMETER PANEL

FIG 11



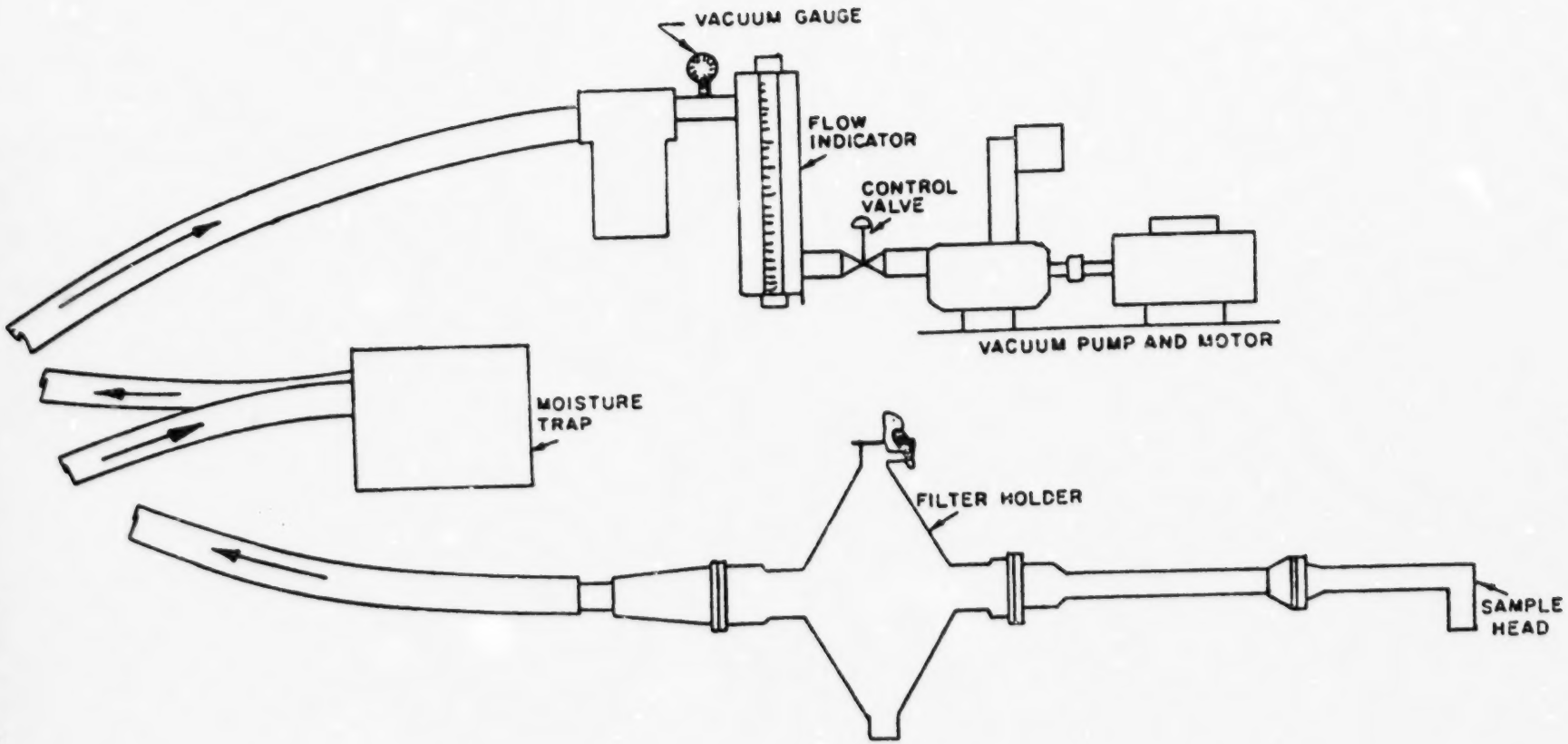
DATALOGGER AND FLUE GAS ANALYSERS

FIG 12



GAS SAMPLING SYSTEM

FIG 13



SCHEMATIC OF DUST SAMPLING SYSTEM

FIG 14